

# Neutrino Velocity and the Variability of Fundamental Constants

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Neutrino speed experiments could be viewed not only as tests of Lorentz invariance but also as measurements of limiting propagation speed for all standard model species below certain depth where no direct metrological information is available. The latter option, hypothetically caused by some chameleon-type background, could be tested in the next installment of the neutrino speed experiments. We also show that complementary constraints on the same class of models can be obtained with experiments testing clock universality in deep underground/underwater experiments. By considering the explicit QED model with particle-universal modification of propagation speed by a depth-dependent tensor background, we show that in general one should expect larger-than-GR shifts of the clock frequencies and clock non-universality. This can be tested by comparison of the narrow transitions in atomic clocks, which for a generic model could deliver a superior accuracy compared to the neutrino speed experiments.

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## I. INTRODUCTION

The OPERA experiment [1] created a stir of theoretical activity by suggesting that the speed of muon neutrino may be higher than the speed of light in vacuum,

$$\epsilon_{\text{OPERA}} \equiv \frac{c_\nu - c_{\gamma, \text{vac}}}{c} = (2.37 \pm 0.32^{+0.34}_{-0.24}) \times 10^{-5}, \quad (1)$$

with the significance of  $\sim 6\sigma$ . These results agree with earlier measurement by the MINOS collaboration [2] that also found  $\epsilon$  to be positive, consistent with (1), and yet consistent with zero at  $2\sigma$ ,

$$\epsilon_{\text{MINOS}} = (5.1 \pm 2.9) \times 10^{-5}. \quad (2)$$

While the claimed OPERA measurement has been shown to result from the initially undetected instrumental error, a new measurement by ICARUS [3] is in perfect agreement with standard physics expectations,

$$\epsilon_{\text{ICARUS}} = (0.01 \pm 0.16 \pm 0.37) \times 10^{-5}. \quad (3)$$

The initial results from OPERA led to the number of experiments testing the neutrino propagation speed, and more results are expected within the short time frame. Given that the neutrino speed experiments are reaching the 10 ppm (or better) accuracy of their measurements of  $c_\nu$ , we ask the question whether such tests have additional physics motivations, given that the original result (1) is incorrect.

In this paper, we shall argue that the neutrino speed measurement provides an interesting probe of fundamental constants at depths that are not yet accessible to direct metrological experiments. While we do not explicitly construct a dynamical model that could give  $\epsilon \sim 10^{-5}$ , we settle for an intermediate framework with the universal density-dependent modification of the limiting propagation speed for all matter species. The purpose of this

note is to point out that additional experiments with ordinary atoms could also test deviations of  $c$  from  $c_{\gamma, \text{vac}}$  deep underground/underwater.

Would continuation of the neutrino speed experiments provide nontrivial probes of Lorentz invariance? Despite last months numerous attempts to construct models that could "fit" the OPERA result, we note that none of the models with density-independent global modification of Lorentz invariance for neutrinos seem to work. Below we summarize the main arguments why large Lorentz violation (LV) for neutrinos is highly unlikely:

1. As pointed out by Cohen and Glashow [4], the neutrino propagation faster than electron's limiting speed at the level of (1) would result in rapid energy loss by neutrinos, which contradicts observations of energetic atmospheric and beam neutrinos. Moreover, if speed of neutrinos is higher than the speed of quarks, a pion would not decay neutrinos above certain energies [5]. Note that the Cohen-Glashow argument applies not only to models that postulate global LV for neutrinos, but also to models that exploit possible local modification of neutrino speed compared to other species caused *e.g.* by a tensor background [6]. (For a divergent point of view see, however, Ref. [7].)
2. Large global violation of Lorentz invariance for neutrinos is in conflict with apparently normal timing of their arrival from the explosion of 1987a supernova.
3. Large global violation of Lorentz invariance for neutrinos is difficult to reconcile with tightly constrained LV parameters for electrons, as the two sectors are connected by the  $W$ -boson loop [8, 9].

On account of these constraints, it is highly unlikely that Lorentz invariance is broken for neutrinos either

globally or locally at such a large level as  $\epsilon \sim 10^{-5}$ . Therefore, the direct measurement of  $c_\nu$  does not provide a superior test of Lorentz invariance for neutrinos. On the other hand, it is possible to speculate [10, 11] that the limiting propagation speed is somehow modified *for all species* in the Earth's interior, and that neutrino speed experiments are the tests of this possibility. The neutrinos in OPERA and ICARUS experiments propagate at average depth of  $\sim 6$  km, reaching  $\sim 11$  km in the middle. There are no direct tests of propagation speed performed at such depths, and therefore a possibility of the common to all particle change in  $c$ , however far-fetched, is not excluded. Therefore, the results (1-3) can be considered as tests of such possibility. One should also recall that gravitational field itself modifies the propagation speed for all species, but the modifications suggested by (1) are many orders of magnitude larger. If indeed a propagation speed is modified at some depth below Earth's surface, one acquires two additional requirements for a model of this type:

4. In-medium modification should sharply decrease near the Earth's surface in order to be in accord with precise measurements of the gravitational force and the limiting propagation speed.
5. Whatever backgrounds modify the propagation speed in the Earth's interior, they should not couple to the 00 component of the stress energy for matter fields in order to avoid larger-than-gravity forces inside planets/stars.

Models where in-medium properties of Lorentz invariant physical parameters such as masses and coupling constants are different from the same values in vacuum were introduced a few years ago [12]. They are related to previous ideas about the modification of the scalar-induced gravitational force by the presence of matter overdensities [13–15]. (Density dependence rather than redshift dependence could be an alternative interpretation of the non-zero result of Ref. [16] that looked for the variation of  $\alpha_{EM}$  in absorption systems at cosmological distances.) Admittedly, models of in-medium modifications of the propagation speed are harder to construct, as they would require "condensation" of fields with non-trivial Lorentz indices.

Assuming for a moment that some variants of density-dependence could modify the limiting propagation speed of neutrinos and all other species, we ask the question whether additional measurements performed with ordinary matter (not neutrinos) could test  $c$  and other constants deep underground/underwater. In the next section we discuss to what extent the (depth-induced) variation of the limiting propagation speed can lead to the variation of coupling constants and clock non-universality, and in the concluding section we propose new experiments that could detect such effects.

## II. LIMITING PROPAGATION SPEED AND CHANGING COUPLINGS

The propagation speed of any matter species can be modified by the non-Lorentz invariant backgrounds. Consider a scalar field, with the Lagrangian modified by some tensor background  $h_{\mu\nu}$ :

$$\mathcal{L}_\phi = \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2}m^2\phi^2 + h_{\mu\nu}\partial_\mu \phi \partial_\nu \phi. \quad (4)$$

Here we do not distinguish between upper and lower indices and perform the Lorentz summations with  $\eta_{\mu\nu} = \text{diag}(1, -1, -1, -1)$ . Moreover, we explicitly work in the system of units where  $\hbar = c = 1$ , and the limiting velocity is 1 if the tensor background  $h_{\mu\nu}$  vanishes. The limiting velocity for the  $\phi$  particle travelling along  $z$  direction ( $E \gg m$ ) is given by

$$c_\phi^2 = \frac{1 - 2h_{zz}}{1 + 2h_{00}} \simeq 1 - 2h_{00} - 2h_{zz}. \quad (5)$$

One can see that negative  $h_{00}$  and/or  $h_{zz}$  can "speed-up" the  $\phi$ -field via effectively stretching time or shortening distances. Besides the simplest possibility (4), one could introduce higher dimensional operators,  $h_{\mu\nu\lambda\kappa}\phi\partial_\mu\partial_\nu\partial_\lambda\partial_\kappa\phi$  that will lead to the energy-dependent modification of the propagation speed.

For the rest of this paper we use the following ansatz for the  $h_{\mu\nu}$  field

$$h_{00} = h_{0i} = 0; \quad h_{ii} = -\epsilon \times \text{diag}(1, 1, 1), \quad (6)$$

so that (4) can be written as  $\mathcal{L}_\phi = \frac{1}{2}(\partial_t \phi)^2 - \frac{1}{2}(1 + 2\epsilon)(\partial_i \phi)^2$ , and we introduce the same modification for all fields of the standard model. The spatial anisotropy of  $\epsilon$  is not a crucial ingredient and is assumed for convenience. To comply with all requirements listed in the introduction, we take  $\epsilon \equiv \epsilon(\text{depth})$  to be some sharp function of the depth, with  $\epsilon = 0$  at the Earth's surface. The initial super-luminal claim by OPERA in our model would imply that at some critical depth  $z_0$  one should assume that  $\epsilon$  deviates from 0 and develops a positive value. The exact relation between  $\epsilon$  in (6) and  $\epsilon_{\text{OPERA}}$  would depend on  $z_0$  in a simple geometric way, but regardless of that measurement (1) would imply  $\epsilon \geq 2.5 \times 10^{-5}$ , while of course (3) is perfectly consistent with  $\epsilon = 0$ .

One could attempt replacing the tensor background (introduced here by hand) with some dynamical scalar, vector, or tensor fields:  $s$ ,  $V_\mu$  or  $H_{\mu\nu}$ . Going over to the canonical normalization of the kinetic terms for these fields, one can write down the interactions modifying the propagation speed of a generic SM field  $\phi$ ,  $M^{-4}(\partial_\mu s \partial_\mu \phi)^2$ ;  $M^{-2}(V_\mu \partial_\mu \phi)^2$ ;  $M^{-1}H_{\mu\nu}\partial_\mu \phi \partial_\nu \phi$  [6]. The immediate problem with the first two constructions is that in order to have any connection with OPERA result, the scale  $M$  would have to be exceedingly low. The most recent model-building attempt to reconcile OPERA measurement with observations [11] employs a scalar

field, and  $M$  has to be below an MeV. Unfortunately, this is in plain contradiction with direct particle physics experiments. (*E.g.* electron-positron scattering remains consistent with the prediction of the SM to energies of  $\sim 100$  GeV, while the double- $s$  exchange 1-loop diagram would lead to the significant modification of scattering for any  $M$  below  $O(10)$  GeV.) The tensor background offers perhaps the only reasonable hope for the dynamical model [6]. Still, even if we leave aside theoretical issues with UV completion, it appears difficult if not impossible to construct a weakly coupled model where dynamical  $H_{\mu\nu}(z)$  follows gravitational potential profile and does not run into contradiction with some observations. The model of Ref. [6] that uses much enhanced coupling of  $H_{\mu\nu}$  to neutrinos faces a problem of Cerenkov radiation of electron-positron pairs, and an attempt to cure it by postulating the same interaction to electrons gives too much "anti-gravitational" force for electrons. For now, we shall assume that there is some consistent framework that leads to the in-medium condensation of  $H_{ij}$  along the lines of the proposals for the scalar field [12, 17], although at this point it is an unproven assumption.

Now we shall consider interacting fields and answer the question of whether the variation of  $\epsilon(z)$  could lead to the non-universality of clocks, or their abnormal speed-up or slow-down with depth, so that it could be picked up with dedicated experiments. (The connection between varying  $c$  and coupling constants was previously discussed in Ref. [18].) For simplicity, let us consider the Lagrangian density of scalar quantum electrodynamics (QED) as a simplest model with gauge interactions, which we shall treat as a proxy to standard model. The unperturbed Lagrangian and its  $\epsilon$ -deformation are given by

$$\mathcal{L}_{\text{QED}} = -\frac{1}{4}F_{\mu\nu}^2 + |(\partial_\mu + igA_\mu)\Phi|^2 - m^2|\Phi|^2 \quad (7)$$

$$\mathcal{L}_\epsilon = h_{\mu\nu}(-F_{\mu\alpha}F_{\nu\alpha} + 2[(\partial_\mu + igA_\mu)\Phi]^*(\partial_\nu + igA_\nu)\Phi) \quad (8)$$

$$- \frac{1}{3}h_{\mu\mu}\left(\delta_1(|D_\mu\Phi|^2 - m^2|\Phi|^2) - \delta_2\frac{1}{4}F_{\mu\nu}^2\right).$$

In these expressions,  $g$  is the gauge coupling and  $D_\mu = \partial_\mu + igA_\mu$  is the covariant derivative, and trace is defined as  $h_{\mu\mu} = h_{\mu\nu}\eta_{\mu\nu}$ . The two free parameters  $\delta_1$  and  $\delta_2$  are meant to be order one, and they parametrize the model dependence. That is, in the first order in  $\epsilon$  their values do not affect the modification of the propagation speed. We now go to the ansatz (6) and take the adiabatic approximation where gradients of  $\epsilon$  are neglected. Then the sum of  $\mathcal{L}_{\text{QED}}$  and  $\mathcal{L}_\epsilon$  gives

$$\begin{aligned} \mathcal{L}_{\text{QED}+\epsilon} = & \mathcal{L}_{\text{int}} + (|\partial_0\Phi|^2 - m^2|\Phi|^2)(1 + \epsilon\delta_1) \\ & - |\partial_i\Phi|^2(1 + \epsilon(2 + \delta_1)) \\ & + \frac{1}{2}\mathbf{E}^2(1 + \epsilon(2 - \delta_2)) - \frac{1}{2}\mathbf{B}^2(1 + \epsilon(4 - \delta_2)), \end{aligned} \quad (9)$$

where we separated terms bilinear in the fields from interactions. As evident from (9), the propagation speeds of photons and charged scalars are the same,  $c_\gamma = c_\Phi = 1 + \epsilon$  up to  $O(\epsilon^2)$  corrections, and independent on  $\delta_{1(2)}$ .

In order to determine whether one should expect abnormal effects with clocks at  $O(\epsilon)$  level, we make redefinitions of fields  $\Phi$  and  $A_\mu$  and distances  $dx_i$ , while leaving the time variable unchanged. Selecting  $A_0 = 0$  gauge, we have:

$$\begin{aligned} \Phi' &= \Phi \left(1 + \frac{\epsilon}{2}(3 + \delta_1)\right); \quad dx' = dx(1 - \epsilon); \\ A'_i &= A_i \left(1 + \frac{\epsilon}{2}(5 - \delta_2)\right). \end{aligned} \quad (10)$$

Making these changes in the action,  $S = \int d^4x \mathcal{L}$ , and dropping primes over  $x$ ,  $\Phi$ ,  $A_i$ , we read off a redefined equivalent Lagrangian to  $O(\epsilon)$  level:

$$\begin{aligned} \mathcal{L}_{\text{QED}+\epsilon} = & -\frac{1}{4}F_{\mu\nu}^2 - m^2|\Phi|^2 \\ & + |(\partial_\mu + ig(1 - \frac{\epsilon}{2}(3 - \delta_2))A_\mu)\Phi|^2. \end{aligned} \quad (11)$$

Thus, we have the same scalar QED theory, but the coupling constant is now changed to

$$\alpha_{\text{eff}} = \left[g(1 - \frac{\epsilon}{2}(3 - \delta_2))\right]^2 = \alpha(1 - \epsilon \times (3 - \delta_2)), \quad (12)$$

and is a function of depth, following the  $\epsilon(z)$  dependence. Notice that we do not have a change in mass of  $\Phi$  as a consequences of us choosing couplings of  $\epsilon$  to  $|\partial_0\Phi|^2 - m^2|\Phi|^2$  combination.

Different coupling constant means that the clocks build from " $\Phi$ -matter" working on the atomic transition of  $\Phi - \Phi^*$  bound state ( $\sim \alpha^2 m$ ) will see the abnormal  $O(\epsilon)$  difference when placed below  $z_0$ . Also, different types of clocks with non-universal dependence on  $\alpha$  will be sensitive to the  $\epsilon$ -induced change of frequencies. Elaborating on this, modification of couplings (12) implies two effects for the atomic clocks. Imagine a hydrogen atom that serves as atomic clock that uses optical and hyperfine transitions,  $\hbar\omega_{\text{opt}} = \frac{3}{8}\alpha^2 m_e c^2$  and  $\hbar\omega_{\text{hf}} = \frac{4g_p m_e}{3m_p}\alpha^4 m_e c^2$ , where we used the proton magnetic  $g_p$  factor, and have restored  $\hbar$  and  $c$  for clarity. Then comparison of the optical or hyperfines frequencies on the surface and underground imply the following ratio of frequencies,

$$\frac{\omega_{\text{opt}}(z < z_0)}{\omega_{\text{opt}}(z = 0)} = 1 - 2\epsilon \times (3 - \delta_2), \quad (13)$$

$$\frac{\omega_{\text{hf}}(z < z_0)}{\omega_{\text{hf}}(z = 0)} = 1 - 4\epsilon \times (3 - \delta_2), \quad (14)$$

while the comparison of optical and hyperfine transition by clocks underground should give a modified ratio:

$$\frac{\omega_{\text{hf}}}{\omega_{\text{opt}}}(z < z_0) = \frac{32g_p m_e}{9m_p}\alpha^2(1 - 2\epsilon \times (3 - \delta_2)). \quad (15)$$

Using Eqs. (13)-(15) as examples it is easy to predict what will happen for arbitrary clocks comparison since alpha dependence has been calculated for all known and proposed clocks -see *e.g.* Ref. [24]. Note that the dependence of the atomic unit of energy  $\alpha^2 m_e c^2$  on  $\epsilon$  (given

in Eq. (13) must be included when calculating dependence of the frequencies on  $\epsilon$ . This dependence was not included in all the previous calculations of alpha dependence in Ref. [24] since the results were presented in atomic units. For the purpose of the present work this dependence can be easily restored by adding factor  $\alpha^2$  to all frequencies calculated in [24]. Then one should replace  $\alpha$  by  $\alpha_{\text{eff}}$  from Eq. (12).

Two things are further worth noticing: firstly, the modification of the limiting propagation speed for two species,  $A_\mu$  and  $\Phi$ , does not carry an unambiguous prediction for  $\alpha_{\text{eff}}$ , as it depends on the free parameter  $\delta_2$  not fixed by the requirement of the universality of  $c$ . On account of that the naive logic "c gets larger so that  $\alpha = g^2/(\hbar c)$  gets smaller" does not hold. Secondly, there is a choice of  $\delta_3 = 3$  when the  $\mathcal{L}_{\text{QED}} \equiv \mathcal{L}_{\text{QED}+\epsilon}$ . This choice corresponds to a situation when  $h_{\mu\nu}$  couples to the electromagnetic stress-energy tensor,  $h_{\mu\nu}T_{\mu\nu}$ , exactly as the linearized gravity would. In this case, to linear order in  $\epsilon$ , the clock universality will be preserved.

Noting that  $\epsilon$  suggested by the original OPERA measurement (1) is very large relative to the precision of modern metrology, it is also interesting to investigate whether coupling of the background to the stress-energy operator would induce clock non-universality in  $O(\epsilon^2)$  order. To that effect, we choose specific values of  $\delta_{1(2)}$ ,

$$\mathcal{L}_{\text{QED}+\epsilon} = \mathcal{L}_{\text{QED}} + h_{\mu\nu}T_{\mu\nu}^{\text{total}}, \quad (16)$$

and follow the similar procedure to find that to  $O(\epsilon^2)$  order this theory is equivalent to

$$\begin{aligned} \mathcal{L}_{\text{QED}+\epsilon} = & \frac{1}{2}(\mathbf{E}^2 - \mathbf{B}^2(1 - 4\epsilon^2)) - m^2|\Phi|^2 \\ & + |(\partial_\mu + ig\left(1 - \frac{3\epsilon^2}{4}\right)A_\mu)\Phi|^2. \end{aligned} \quad (17)$$

Notice that the modification (16) creates  $O(\epsilon^2)$  non-universality in the propagation speed of  $A_\mu$  and  $\Phi$ , and this is why the  $\epsilon^2$ -dependence persists for the free fields. Even if one neglects magnetic effects, the coupling constant is modified at  $O(\epsilon^2)$  level. Only the full general-relativity-(GR)-like extension  $\eta_{\mu\nu} \rightarrow \eta_{\mu\nu} + h_{\mu\nu}$  of the original theory would preserve clock universality, which would entail additional  $O(h_{\mu\nu}^2)$  terms in (16) with specific coefficients. Thus, on the basis of (11) and (17), we conclude that barring a very special GR-like case, the modification of the limiting propagation speed for particles leads to the clock non-universality.

### III. DISCUSSION: TESTING CLOCKS AT LARGE DEPTHS

We have shown that one logical possibility - depth-dependent modification of  $c$  for all species - is not immediately ruled out by the variety of constraints on LV and by gravity tests. Moreover, such possibility can be tested with the neutrino speed experiments. With the

expansion of the baseline it is conceivable to probe the propagation speed as deep as  $O(100 \text{ km})$ .

The purpose of this paper was not to build an explicit dynamical model with *e.g.* condensation of spin-2 fields, but to investigate whether depth-induced modification of the maximum propagation speed can be seen with more conventional means other than timing of neutrino events. We have shown that with a unique exception of pure GR-like coupling, one should expect an  $O(\epsilon)$  (or  $O(\epsilon^2)$  in case of  $h_{\mu\nu}T^{\mu\nu}$  coupling) deviations of couplings from their "surface" values, spatially linked to the deviation of propagation speed. An assumption that building a self-consistent dynamical models of this kind is possible is of course a "leap of faith", and several arguments can be presented why this is difficult to achieve.

Over the years, there has been a concerted effort to test the GR theory in space [19]. Here we argue that the OPERA, MINOS and ICARUS results can be viewed as first metrological tests reaching 11 km underground. They give further incentives to test clock universality and their abnormal speed-up/slow-down at great depths. The GR-caused change in the frequency of clocks at depth  $h$  and on the surface is given by  $gh/c^2$  and for  $h \sim 10 \text{ km}$  is  $\Delta\omega/\omega \sim 10^{-12}$ . Even the  $\epsilon_{\text{OPERA}}^2$ -size effect is larger than GR shift by several orders of magnitude. Leaving aside the issue of the neutrino velocity, we believe that precision measurements underground are justified in their own right, as no systematic tests of this kind were ever performed.

One could envisage two types of experimental set-ups to test the constants-changing-with-depth conjecture. First one could use the existing stable frequency emitters with known dependence on fundamental constants. Lowering them at great depths and comparing their frequencies either in-situ or by transmitting the signals to the surface will test clock universality. The second set-up uses two identical clocks synchronized on the surface, with one of them brought deep underwater/underground for a period of time, with eventual comparison of time measured by both clocks upon the return. Should any of such experiments indeed detect larger-than-GR effects of the depth on clocks, one could also experimentally determine  $z_0$ , and further investigate possible large gradient effects around  $z = z_0$ .

The deep underground locations could be used as a starting point for such tests. Indeed, deepest mines used for the underground science, such as *e.g.* Sudbury mine reach depths of 2 km. Similar depths in ice are reached by the IceCube collaborations operating at the South Pole. The deepest commercial used mines in South Africa extend 3.9 km underground. Ultimately, the "dream location" for such tests could be deep oceanic trenches and the deepest boreholes that extend as deep as 11 km or more (which is incidentally very close to the maximum depth along the OPERA and ICARUS neutrino trajectory).

The connection between variations of the fundamental constants and the variation of the dimensionless ratios of

the transition frequencies of different atomic clocks is a well-researched subject. Current experimental sensitivity to the variation of  $\alpha$  is better than 1 part in  $10^{16}$  [20–23] per year, far exceeding accuracy needs discussed in this paper. To check the link between the OPERA anomaly and variation of the fundamental constants it would be sufficient to compare commercially available  $Cs$ ,  $Rb$  or quartz clocks which have accuracy  $10^{-11} - 10^{-12}$ . The sensitivity of such clocks to the variation of the fundamental constants has been calculated in [24]. Further six orders of magnitude improvement in sensitivity may be reached using optical clocks and the frequency comb, as well as with the use of atomic systems with closely degenerate levels [25].

Finally, we would like to comment that the density

for many atomic clocks is very low, so that the question arises whether this would restore "surface values" for couplings inside atomic clocks deep underground. This question was answered in the models of chameleon-like varying constants [12], where it was shown that the realistic model parameters ensure that the attainable sizes of the cavity are much less than the Compton wavelength of the chameleon field. In this case, the surface values for couplings will not be restored within the clock volume, if it is placed in an environment of non-zero  $\epsilon$ .

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